

Advanced Mirror Technology Development (AMTD) Project: Overview and Year 4 Accomplishments

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ABSTRACT

The Advanced Mirror Technology Development (AMTD) project is in Phase 2 of a multiyear effort initiated in Fiscal Year (FY) 2012, to mature toward the next Technology Readiness Level (TRL) critical technologies required to enable 4-m-or-larger monolithic or segmented ultraviolet, optical, and infrared (UVOIR) space telescope primary-mirror assemblies for general astrophysics and ultra-high-contrast observations of exoplanets. Key hardware accomplishments of 2015/16 are the successful low-temperature fusion of a 1.5-meter diameter ULE mirror that is a 1/3rd scale model of a 4-meter mirror and the initiation of polishing of a 1.2-meter Extreme-Lightweight Zerodur mirror. Critical to AMTD's success is an integrated team of scientists, systems engineers, and technologists; and a science-driven systems engineering approach.

Keywords: space telescopes, astrophysics, astronomy, ATLAST, LUVOIR, HabEx.

1. INTRODUCTION

UVOIR measurements provide robust, often unique, diagnostics for investigating astronomical environments and objects. UVOIR observations are responsible for much of our current astrophysics knowledge and will produce as-yet-unimagined, paradigm-shifting discoveries. A new, larger UVOIR telescope is needed to help answer fundamental scientific questions such as:

- Does life exist on nearby Earth-like exoplanets?
- How do galaxies assemble their stellar populations?
- How do galaxies and the intergalactic medium interact?
- How did planets and smaller bodies in our own solar system form and evolve?

According to the 2010 Decadal Survey¹: New Worlds, New Horizons in Astronomy and Astrophysics (NWNH), an advanced, large-aperture UVOIR telescope is required to enable the next generation of compelling astrophysics and exoplanet science. NWNH also noted that present technology is not mature enough to affordably build and launch UVOIR telescopes, diffraction-limited at visible or shorter wavelengths, with apertures larger than 4 m. According to the 2012 NASA Space Technology Roadmaps and Priorities report², the highest priority technology in which NASA should invest to enable “*Objective C: Expand our understanding of Earth and the universe in which we live,*” is a new generation of low-cost, stable astronomical telescopes for high-contrast imaging and faint-object spectroscopy to “*Enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects.*” Finally, according to the NASA Office of Chief Technologist Science Instruments, Observatory, and Sensor Systems Technology Assessment Roadmap³, technology to enable a future UVOIR or high-contrast exoplanet mission needs to be at TRL6 by 2018, so a viable flight mission can be proposed to the 2020 Decadal Survey.

AMTD's objective is to mature towards TRL6 technologies to enable large UVOIR space telescopes. Because future missions may require either monolithic or segmented architectures, AMTD is pursuing technologies that enable both.

Phase 1 advanced technology readiness of six key technologies required to make an integrated primary mirror assembly (PMA) for a large aperture UVOIR space telescope.

- *Large-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates*
- *Support System*
- *Mid/High-Spatial Frequency Figure Error*
- *Segment Edges*
- *Segment-to-Segment Gap Phasing*
- *Integrated Model Validation*

Phase 2 is continuing these efforts with three clearly defined milestones:

- *Fabricate a 1/3-scale model of 4-m class 400-mm thick deep-core ULE[®] mirror* to demonstrate lateral scaling of the deep-core process.
- *Characterize two candidate primary mirrors* (the 1/3-scale mirror and a 1.2-m Extreme Lightweight Zerodur[®] Mirror owned by Schott) by measuring their modal performance and optical performance from 250 to 300K.
- *Add capabilities and validate integrated design and modeling tools* to predict the mechanical and thermal behavior of the candidate mirrors; validate models; generate Pre-Phase-A point designs; and predict on-orbit optical performance.

AMTD results were presented at Mirror Tech Days 2015 and published in proceedings of the 2015 SPIE Optics and Photonics Conference (References 4 to 10).

2. PROGRESS AND ACCOMPLISHMENTS

2.1 Large-Aperture, Low-Areal-Density, High-Stiffness Mirror Substrates

Need: To achieve the ultra-stable mechanical and thermal performance required for high-contrast imaging, both (4-m to 8-m) monolithic and (8-m to 16-m) segmented primary mirrors require larger, thicker, and stiffer mirror substrates.

Accomplishment: During FY 2015/16, AMTD Phase 2 progressed this technical area by successfully fusing the 1.5-meter ULE[®] substrate, continuing to develop the Arnold Mirror Modeler and using the AMM to develop candidate point designs for a potential HabEx mission.

Deep Core Mirror Substrate Technology: As previously reported, in Phase 1 AMTD partner Harris Corporation demonstrated a new five-layer ‘stack & fuse’ process for fabricating deep-core mirror substrates. Phase 1 made a 43-cm-diameter ‘cut-out’ of a 4-m-diameter, 40-cm thick, $< 45 \text{ kg/m}^2$ mirror substrate. In FY 2014/15 of Phase 2, Harris designed a 1.5-m x 165 mm, 400 Hz first mode mirror. To demonstrate scalability, a 4-meter mirror monolithic mirror was designed and scaled down to 1.5-meters. The design incorporated multiple proprietary lessons-learned from the 40-cm deep-core mirror to enhance manufacturability and insure launch survival. While one would not use the stack & fuse technology for a 1.5-m class mirror, it is sufficient to demonstrate scalability. Note that a single core layer version of this 400 Hz mirror would meet the performance needs for a 12 to 16-m segmented aperture telescope.

In FY 2015/16, Harris fabricated the mirror’s components (faceplate, 18 core elements and backplate), then fused them together to form a planar substrate (Figure 1a). Before fusing, Harris used proprietary modeling tools to predict the visco-elastic performance of the mirror (Figure 1b). Proprietary post-fusing data was acquired to validate by test the visco-elastic model predictions. In FY 2016/17, the substrate will be replicated to a sphere, polished, and its mechanical and thermal performance characterized. Finally, its internal structure will be measured via 3D x-ray tomography.

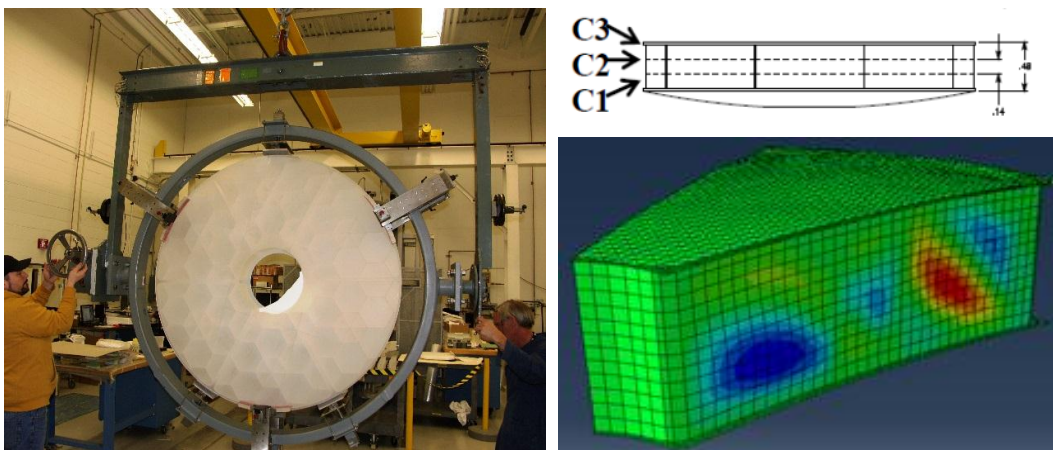


Figure 1: “1/3rd mirror” (1.5-meter x 165 mm) fabricated using stacked core technology and traceable to a full 4-meter mirror. (a) fused substrate; (b) visco-elastic deformation prediction.

Arnold Mirror Modeler: Development of the Arnold Mirror Modeler tool for rapid creation and analysis of detailed mirror designs continues. The Modeler creates a complete analysis stream, including model, loads [static and dynamic], plots and a summary file of input variables and results suitable for optimization or trade studies. Values of all settings can be archived and recalled to continue or redo any configuration. In FY15/16 capabilities added include (Figure 2): 1) SOFIA ‘style’ shaped substrates, T-ribs for stiffer open back mirrors, elliptical apertures and asymmetric substrates for off-axis monolithic mirrors; 2) hex and petal segmented mirrors; and 3) standard check cases for ANSYS, ABAQUS and NASTRAN. Progress related to mount systems and support structures will be discussed below. Finally, approval from NASA was obtained to make the tool available to US Government contractors.

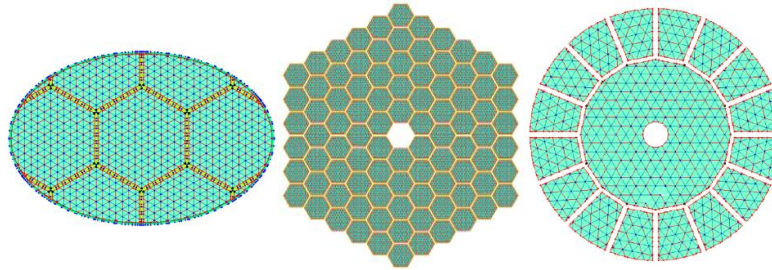


Figure 2: Elliptical, Hex Segmented and Petal Segmented Mirror Designs.

4-meter Point Design: In support of a potential HabEx mission, multiple point designs for candidate 4-m mirrors were performed. For a mass constrained mission (i.e. launched via Delta-IVH) design concepts for a 900-kg 4-m mirror with 100 Hz first mode were developed. For a mission to be launched via an SLS, design options were studied for making stiffer mirrors by relaxing the mass constraint (Table 1). It is interesting to note that JWST’s 1.5-m segments have a 200 to 220 Hz first mode frequency and HST’s 2.4-m mirror has a 260 to 280 Hz first mode.

Table 1: 4-meter Mirror Point Designs				
Thickness [m]	0.40	0.45	0.6	0.75
Mass [kg]	900	2200	2560	2860
First Mode [Hz]	100	180	215	245

2.2 Support Systems

Need: Large-aperture mirrors require support systems to survive launch and deploy on-orbit stress-free and undistorted. Additionally, segmented mirrors require large structure systems that establish and maintain the mirror’s shape.

Accomplishment: During FY 2015/16, AMTD progressed this technical area by continuing to develop mount capabilities in the Arnold Mirror Modeler.

Arnold Mirror Modeler: In FY15/16 capabilities added include: 1) hexapod systems for curved back segmented apertures; 2) automatic mount pad locator; and 3) support systems for elliptical mirrors. As segmented mirror diameter increases, it becomes desirable to define the segment support system attachment plane as a curve (Figure 3). Such a support system provides a more uniform strut stiffness for dynamic behavior. For ease of design, an algorithm that locates the mount pads aligned exactly with the center of a cell or the intersection of cell webs was added (Figure 4).

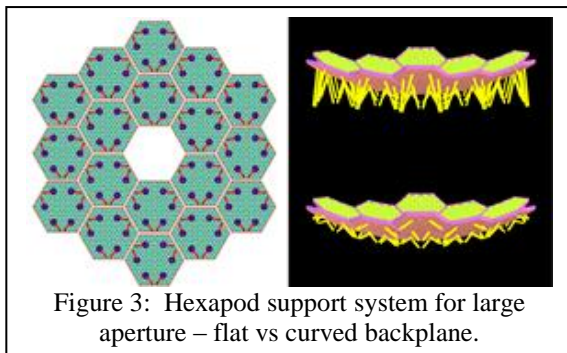


Figure 3: Hexapod support system for large aperture – flat vs curved backplane.

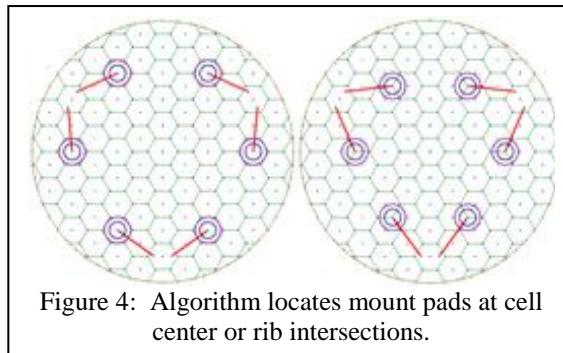


Figure 4: Algorithm locates mount pads at cell center or rib intersections.

A hexapod interface works well with symmetric mirrors. But, HabEx is considering an elliptical off-axis mirror. Such a mirror requires a different system to provide launch and on-orbit performance (Figure 5). AMM models such a system.

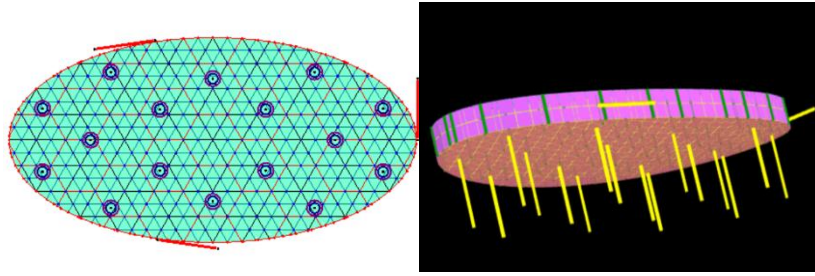


Figure 5: Launch support and on-orbit support systems for off-axis elliptical mirrors.

2.3 Segment-to-Segment Gap Phasing

Need: To avoid speckle noise which can interfere with exoplanet observation, internal coronagraphs require an ultra-stable wavefront. And for a segmented mirror this means stable segment to segment phasing.

Accomplishment: During FY 2015/16, AMTD progressed this technical area by continuing our systems engineering effort to understand the interaction between optical telescope wavefront stability and coronagraph contrast leakage.

Contrast Leakage versus Segmentation: In support of a potential LUVOR mission, in FY14/15 AMTD analysis how segment to segment piston and tip/tilt motion affected contrast leakage for a 4th order Lyot coronagraph as a function of number of segment rings. Leakage was 10X more sensitive to piston than tip/tilt was reported. In FY15/16, this analysis was refined to correct a normalization error and now report that leakage is 2.5X more sensitive to piston than tip/tilt (Figure 6). An intuitively obvious observation is that tip/tilt leakage as a function of λ/D distance has a clear dependence on the number of segment rings – D/N segment spatial frequency scatters energy into $N \lambda/D$.

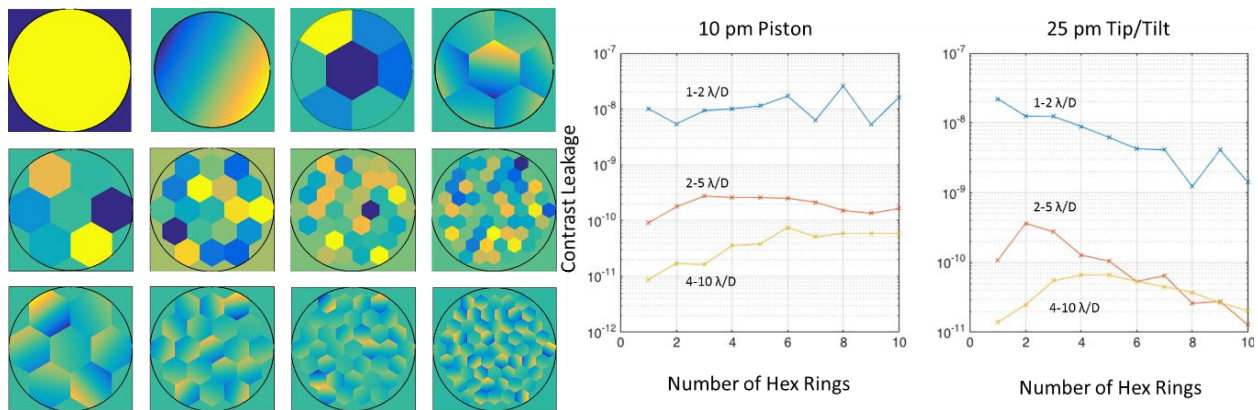


Figure 6: 4th Order Coronagraph Contrast Leakage for Piston and Tip/Tilt as function of Segmentation.

Contrast Leakage for an Apodized Coronagraph: In support of a potential LUVOR mission, in FY15/16, the contrast leakage of an apodized shaped pupil mask coronagraph, specifically designed for a JWST style segmented aperture, (N'Diaye, et. al., “Apodized Pupil Lyot Coronagraphs for Arbitrary Apertures”, Astro-PH, 2016), was analyzed as a function of primary and secondary mirror motion. Coronagraph leakage was calculated for nine misalignment states (left to right in Figure 7): PM segment piston, PM segment tip/tilt, PM segment power, SM decenter, PM segment trefoil, PM segment astigmatism, PM or SM radius error, PM backplane bending, and PM or SM spherical error.

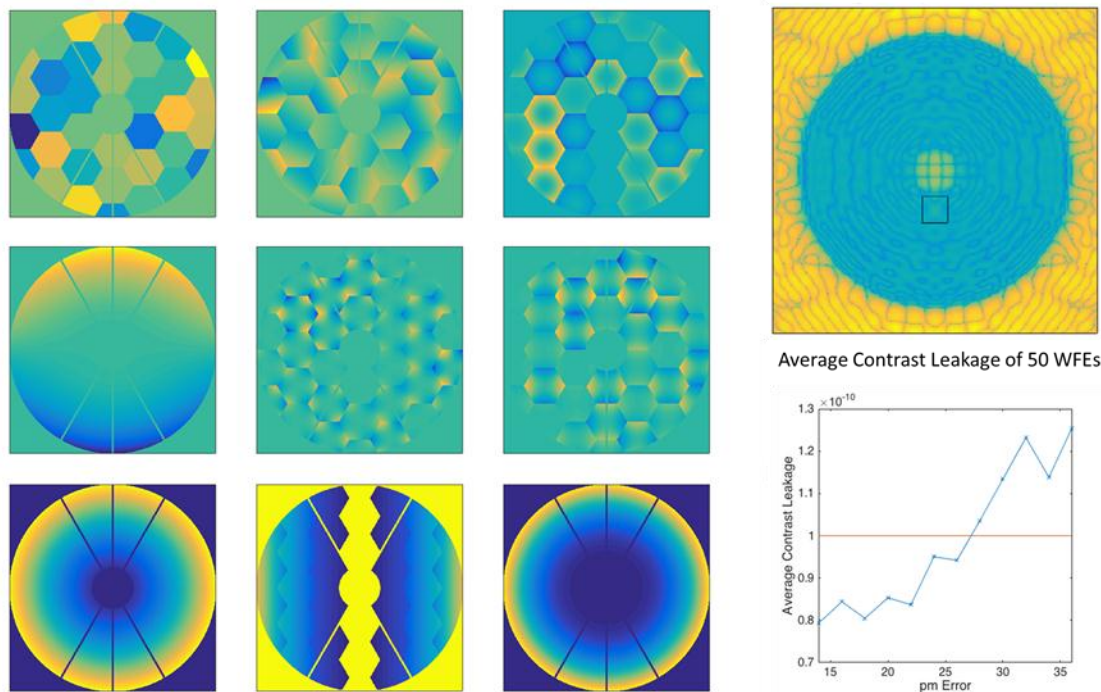


Figure 7: Maximum amplitudes each misalignment error are defined to be when average contrast leakage over 4 to $6\lambda/D$ regions of interest of 10^{-10} .

Leakage sensitivity for each error was determined by averaging 50 random realizations. The maximum allowed amount for each error was defined to be when the average contrast leakage in the 4 to $6\lambda/D$ region of interest is 10^{-10} . Table 2 summarizes our findings. Note: The backplane X/Y difference is a result of the localized region of interest.

Table 2: Misalignment Error Amplitude for 10^{-10} Average Contrast Leakage of Apodized Coronagraph									
Segment Errors					Secondary Mirror			Backplane	
Piston	Tip/Tilt	Power	Astig	Trefoil	Power	Coma	Sphere	X-Bend	Y-Bend
10 pm	20 pm	30 pm	35 pm	65 pm	3000 pm	5800 pm	500 pm	500 pm	120 pm

2.4 Integrated Model Validation

Need: On-orbit performance is driven by mechanical stability (both thermal and dynamic). As future systems become larger, compliance cannot be fully tested; performance verification will rely on results from a combination of sub-scale tests and high-fidelity models. It is necessary to generate and validate as-built models of representative prototype components to predict on-orbit performance for transmitted wavefront, point spread function (PSF), pointing stability, jitter, thermal stability, and vibro-acoustic and launch loads.

Accomplishment: During FY 2015/16, AMTD progressed this technical area by continuing our systems engineering effort to understand the interaction between optical telescope thermal environment and wavefront stability, and by continuing our preparation for thermal vacuum testing of the 1.5-meter ULE[®] and the 1.2-meter Zerodur[®] mirrors.

Thermal Stability: In FY 2014/15, a new methodology was developed and presented for understanding how a primary mirror responds to a dynamic thermal environment. This tool showed that the wavefront error (WFE) for a 4-m ULE[®] primary mirror with $\sim 50 \text{ kg/m}^2$ areal mass remains below 10 pm for a 50 mK thermal oscillation of period shorter than 70 seconds. In FY 2015/16, this relationship was further explored as a function of a telescope's thermal sensitivity (i.e. its WFE response in nm rms per mK-second of thermal change). Modeling indicates that WFE can meet the desired stability when the primary mirror is inside a thermally controlled environment whose period and controllability meet the specifications shown in Figure 8. Controllability is the maximum deviation of the shroud's temperature from the average temperature. Period of the control system is the time it takes for a heater cycle. Thermal sensitivity depends on factors such as mirror material CTE and conductivity, mirror geometry and mass, etc.

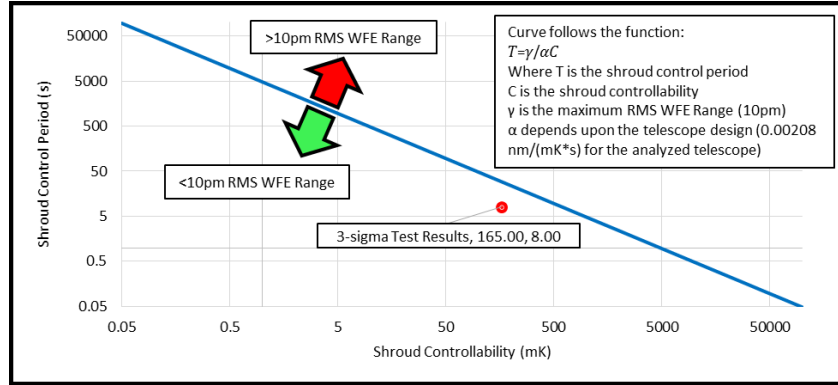


Figure 8: For a given Telescope, its wavefront stability can be kept below a specified value by varying Shroud Controllability and Cycle Period.

Integrated modeling shows that the RMS WFE range is linearly proportional to the mirror's coefficient of thermal expansion (CTE) and inversely proportional to the mirror's mass ($V\rho$) and specific heat (c_p). A closed-form derivation found similar relationships between thermal parameters and the thermal strain rate caused by a heat imbalance:

$$\frac{dL}{dt} = \frac{(CTE)L}{V\rho c_p} \frac{dQ}{dt}$$

Based upon these two findings, two figures of merit for thermally stable mirror materials are defined:

$$\text{Massive Active Opto-Thermal Stability, } MAOS = \frac{c_p \rho}{CTE}$$

$$\text{Active Opto-Thermal Stability, } AOS = \frac{c_p}{CTE}$$

Selecting a mirror substrate with a higher MAOS and AOS will result in a lower thermal strain rate in the mirror, i.e. a slower WFE change rate.

Thermal Vacuum Test Preparation: A key objective of AMTD is to validate-by-test integrated model thermal performance predictions. To enable testing of short radius of curvature mirrors in the MSFC XRCF, a pressure tight enclosure (PTE) was built to place at the mirror's center of curvature: an interferometer to measure surface figure, an absolute distance meter to measure radius of curvature and a thermal camera to measure front surface temperature distribution (Figure 9). The PTE has two windows: one for the interferometer and ADM and a second for the infrared camera. In FY 2016/17, chamber qualification will be conducted to test and then characterize the static thermal performance of the 1.5-meter ULE© and the 1.2-meter Zerodur© mirrors from 250K to 300K.

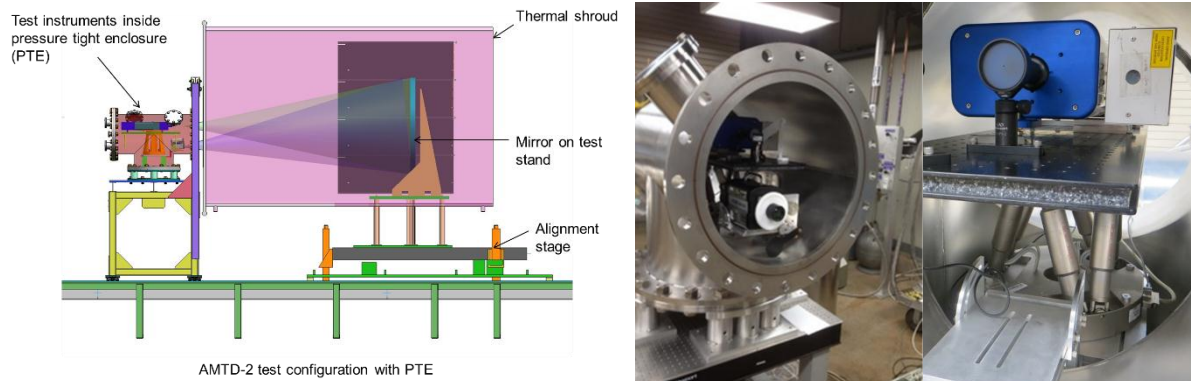


Figure 9: Pressure Tight Enclosure enable center of curvature testing of mirror's radius of curvature, surface figure and front surface thermal gradient.

3. CONCLUSIONS

The Advance Mirror Technology Development (AMTD) project is a multi-year effort to mature towards TRL-6 technologies needed to enable 4 to 8 meter UVOIR space telescope primary mirror assemblies for both general astrophysics and ultra-high contrast observations of exoplanets. AMTD uses a science-driven systems engineering approach. We mature technologies required to enable the highest priority science AND result in a high-performance low-cost low-risk system. To provide the science community with options, we are pursuing multiple technology paths including both monolithic and segmented space mirrors. AMTD continues to make measurable progress against defined milestone metrics.

ACKNOWLEDGEMENTS

ATMD is a funded NASA Strategic Astrophysics Technology project.

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